Ocean Modeling in CCS-2

Mark R. Petersen

Outline

- The POP ocean model

- The IPCC climate change assessment

- Sub-grid scale turbulence parameterizations

- Overflows in the thermohaline circulation

CO$_2$ ice core record

currently: 380 ppm

Homo sapiens neanderthalensis

Homo sapiens sapiens

Homo sapiens archaic

Homo erectus

domesticated plants & animals

Siegenthaler et.al. *Science* 2005
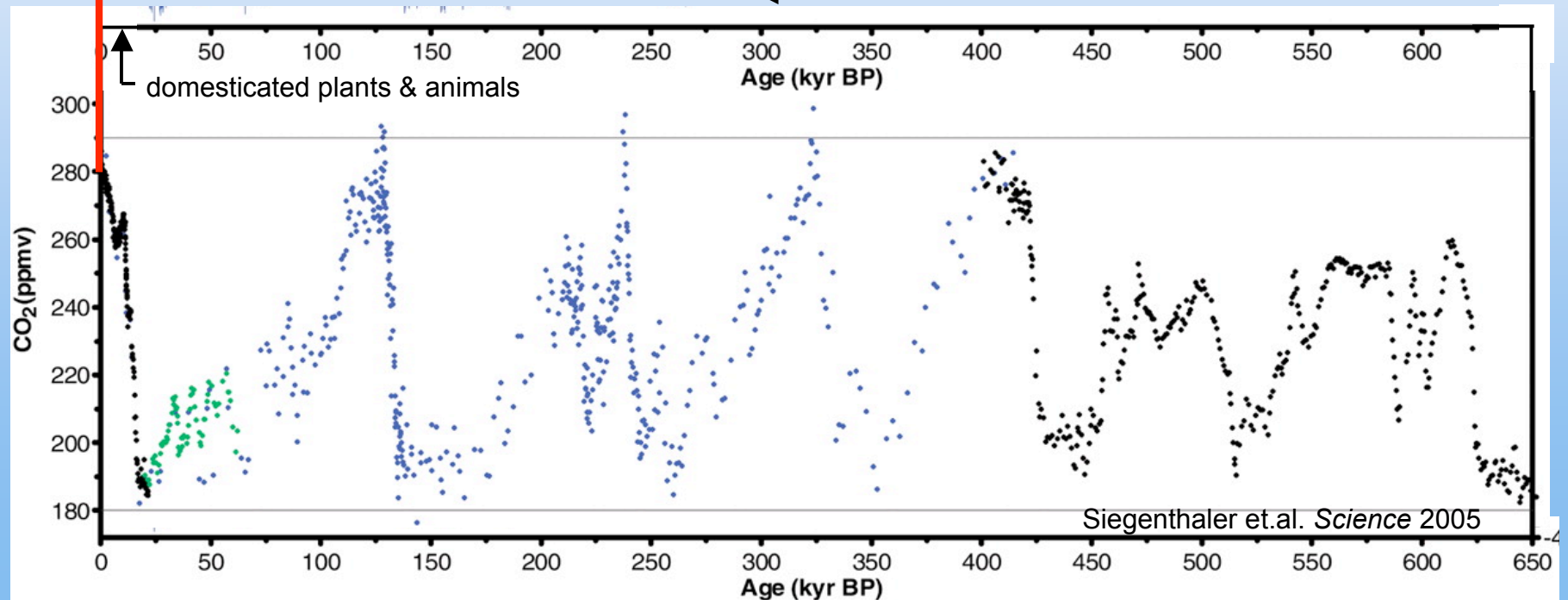
Community Climate System Model

Atmosphere (NCAR)

Land Surface (NCAR)

Flux Coupler

Ocean POP (LANL)

Sea Ice (LANL)
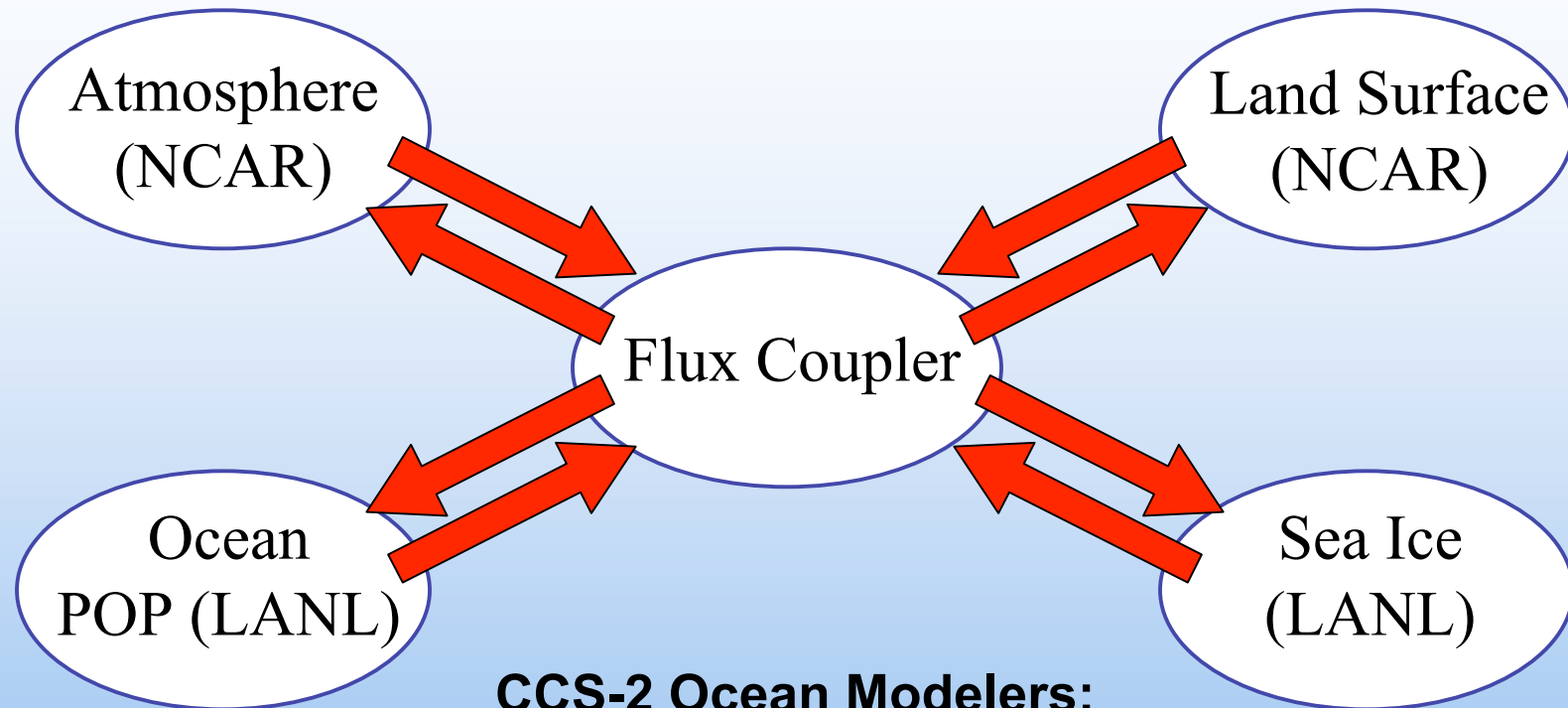
CCS-2 Ocean Modelers:

Sumner Dean
Scott Elliot
Matthew Hecht
Bob Malone

Balu Nadiga
Mark Petersen
Wilbert Weijer
Beth Wingate

Other ocean and sea ice modelers are in T-3 and EES

Parallel Ocean Program (POP)

- Solves conservation equations at each grid-point and time-step:

conservation of momentum

$$\partial_t \mathbf{u} + \underbrace{\mathbf{u} \cdot \nabla \mathbf{u}}_{\text{advection}} - \underbrace{f \times \mathbf{u}}_{\text{Coriolis}} = \underbrace{-\rho_0^{-1} \nabla p}_{\text{pressure gradient}} + \underbrace{A_M \nabla_h^2 \mathbf{u} + \partial_z \mu \partial_z \mathbf{u}}_{\text{diffusion}}$$

conservation of mass for incompressible fluid

$$\nabla_h \cdot \mathbf{u} + \partial_z w = 0$$

conservation of tracers (temperature, salinity)

$$\partial_t \varphi + \underbrace{\mathbf{u} \cdot \nabla \varphi}_{\text{advection}} = \underbrace{A_H \nabla_h^2 \varphi + \partial_z \kappa \partial_z \varphi}_{\text{diffusion}} + \underbrace{Q}_{\substack{\text{source/}\\\text{sink}}}$$
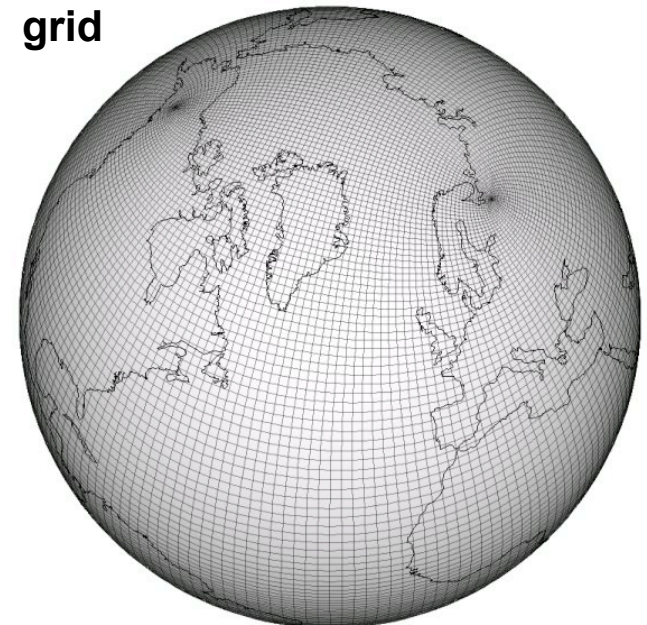
hydrostatic in the vertical

$$\frac{\partial p}{\partial z} = -\rho g$$

equation of state

$$\rho = \rho(T, S, p)$$

|	
$\mathbf{u}$	hor. velocity w
	vertical velocity
φ	tracer
t	time
p	pressure
ρ_0	density
T	temperature
S	salinity

grid

POP: 0.1º resolution, speed
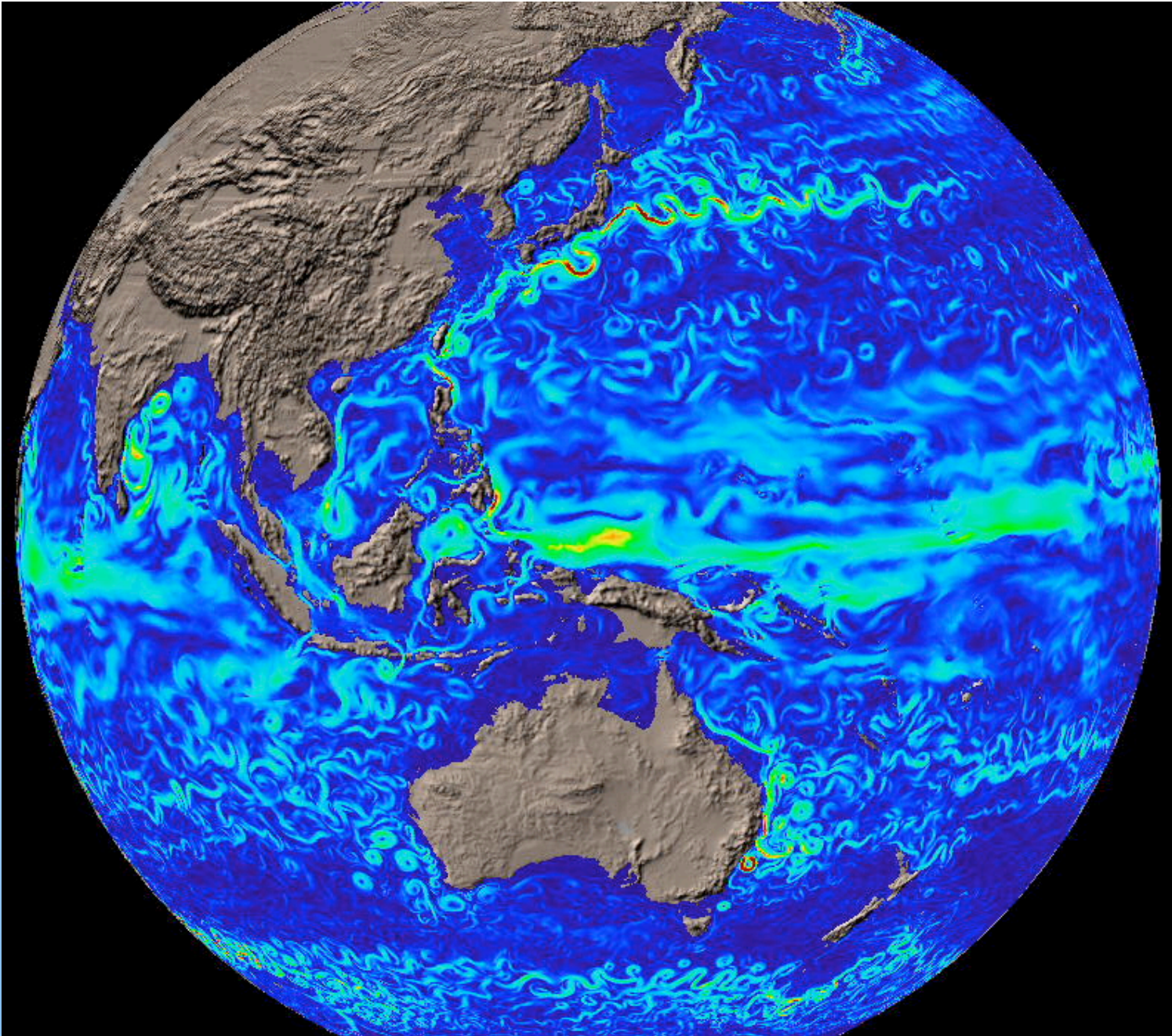
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IPCC - Intergovernmental Panel on Climate Change

- Created in 1988 by
  - World Meteorological Organization (WMO)
  - United Nations Environment Programme (UNEP)

- Role of IPCC: document the scientific consensus of:
  - the **scientific basis** of risk of human-induced climate change
  - its potential **impacts** and
  - options for **adaptation and mitigation**.

- Main activity: Assessment reports
  - Third Assessment Report: 2001
  - Fourth Assessment Report: 2007
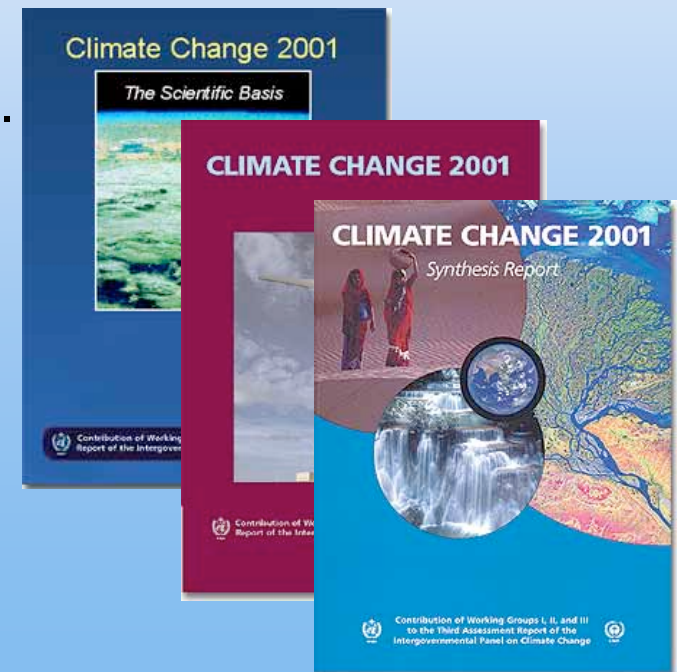
Climate Change 2001

The Scientific Basis

Contribution of Working Group I to Report of the Intergovernmental Pa...

Contents

IPCC scenarios of future emissions

	A: *slower* conversion to clean & efficient technologies	B: *faster* conversion to clean & efficient technologies
1: global population levels off, declines after 2050	**A1FI**: fossil intensive **A1T**: non-fossil intensive **A1B**: balance of F&T	**B1**
2: continuously increasing population	**A2**	**B2**

IS92a: business as usual (extrapolation from current rates of increase)

economic models

carbon cycle models

(a) CO$_2$ emissions
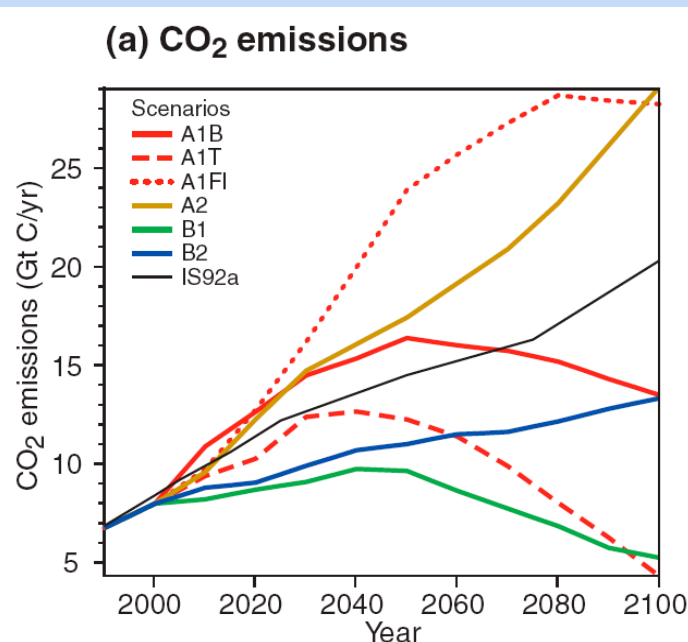
(b) CO$_2$ concentrations
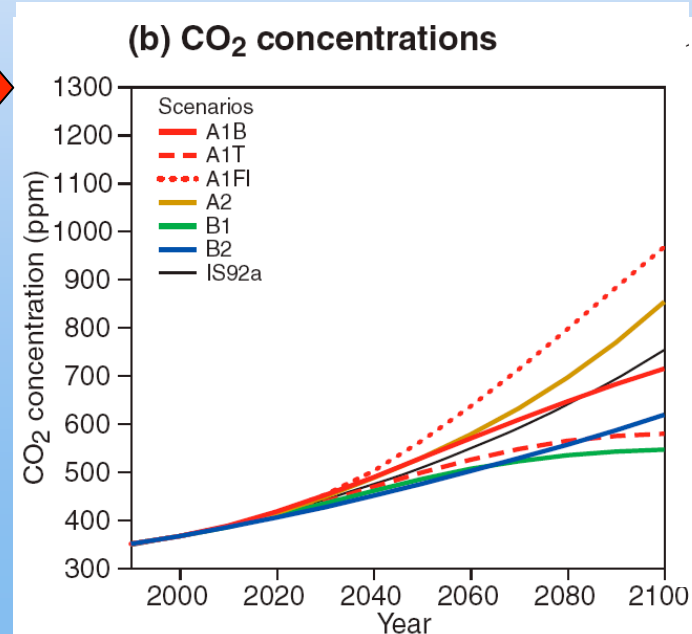
scenarios

	A: *slower* conversion to clean & efficient technologies	B: *faster* conversion to clean & efficient technologies
1: global population levels off, declines after 2050	**A1FI**: fossil intensive **A1T**: non-fossil intensive **A1B**: balance of F&T	**B1**
2: continuously increasing population	**A2**	**B2**

economic models
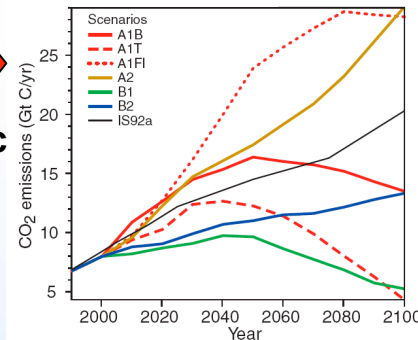
CO₂ emissions

CO₂ concentration

carbon cycle models
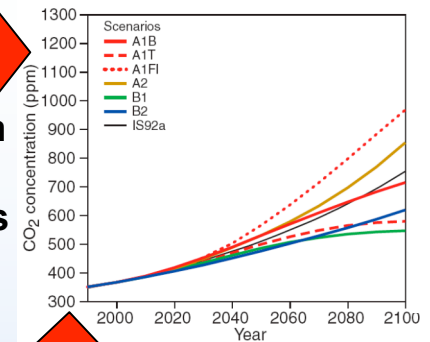
ensemble of climate models

Temperature change scenario A2

average of ensemble

Final product
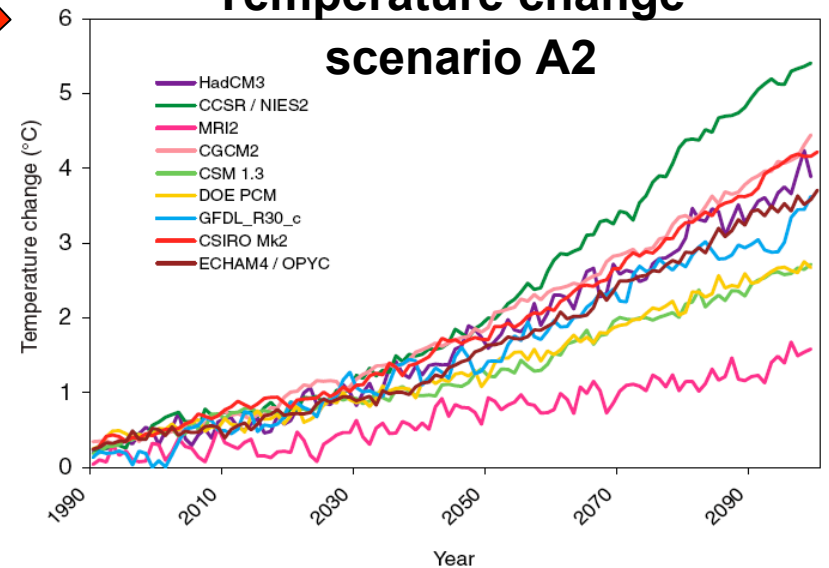
Ensemble mean: Regional temperature changes

scenario A2

central US:
5°C (9°F)

temperature change, °C

color shading: ensemble mean
change of temperature,
2071 to 2100 mean
relative to
1960 to 1990 mean

blue lines: range of
temperature change
within ensemble
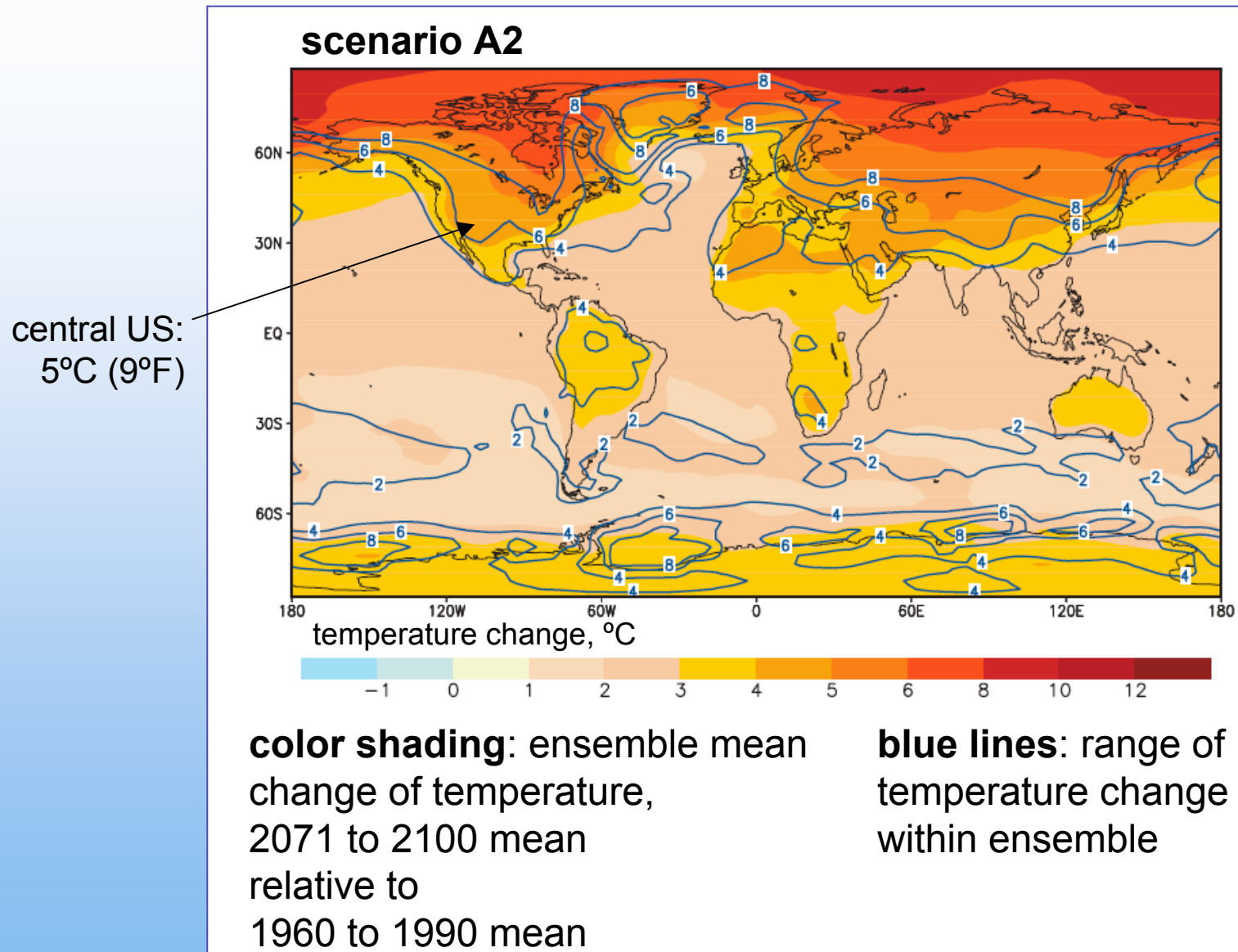
IPCC 2001: Estimates of confidence

Table 4: Estimates of confidence in observed and projected changes in extreme weather and climate events. The table depicts an assessment of confidence in observed changes in extremes of weather and climate during the latter half of the 20th century (left column) and in projected changes during the 21st century (right column)[a]. This assessment relies on observational and modelling studies, as well as physical plausibility of future projections across all commonly used scenarios and is based on expert judgement (see Footnote 4). [Based upon Table 9.6]

Confidence in observed changes (latter half of the 20th century)	Changes in Phenomenon	Confidence in projected changes (during the 21st century)
Likely	Higher maximum temperatures and more hot days over nearly all land areas	Very likely
Very likely	Higher minimum temperatures, fewer cold days and frost days over nearly all land areas	Very likely
Very likely	Reduced diurnal temperature range over most land areas	Very likely
Likely, over many areas	Increase of heat index[8] over land areas	Very likely, over most areas
Likely, over many Northern Hemisphere mid- to high latitude land areas	More intense precipitation events[b]	Very likely, over many areas
Likely, in a few areas	Increased summer continental drying and associated risk of drought	Likely, over most mid-latitude continental interiors (Lack of consistent projections in other areas)
Not observed in the few analyses available	Increase in tropical cyclone peak wind intensities[c]	Likely, over some areas
Insufficient data for assessment	Increase in tropical cyclone mean and peak precipitation intensities[c]	Likely, over some areas

[a] For more details see Chapter 2 (observations) and Chapters 9, 10 (projections).

[b] For other areas there are either insufficient data of conflicting analyses.

[c] Past and future changes in tropical cyclone location and frequency are uncertain.

[8] Heat index: A combination of temperature and humidity that measures effects on human comfort
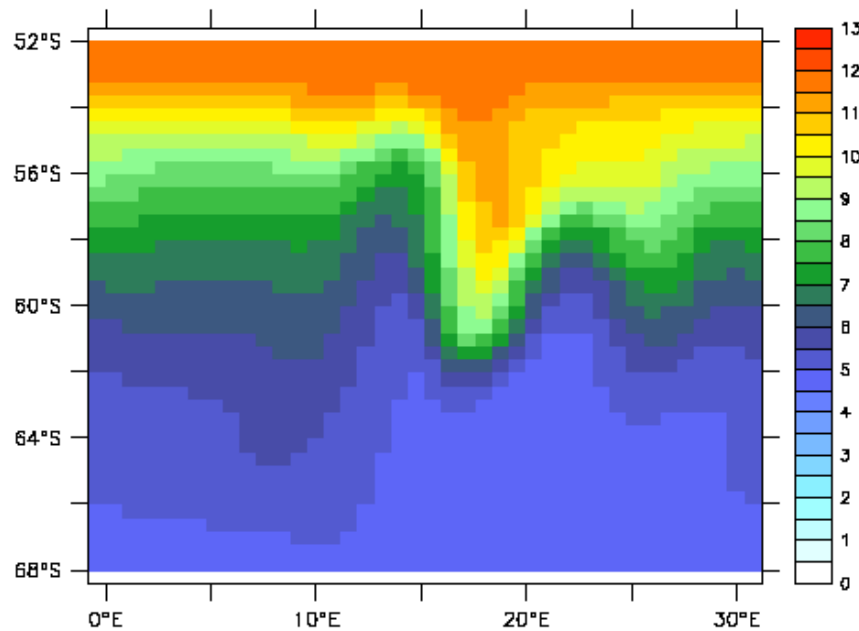
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Parallel Ocean Program (POP)

Resolution is costly, but critical to the physics
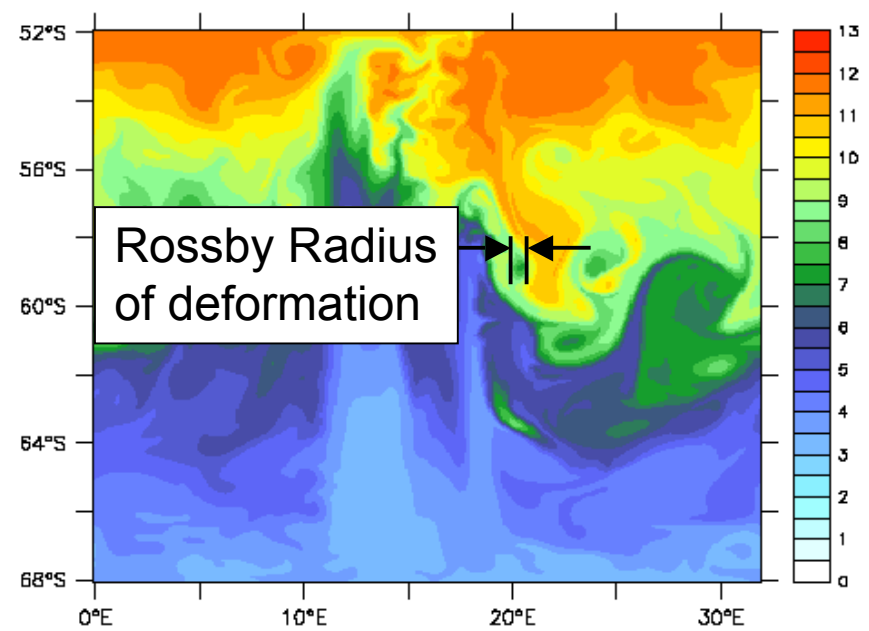
Climate simulations

- low resolution: 1 deg (100 km)
- long duration: 100s of years
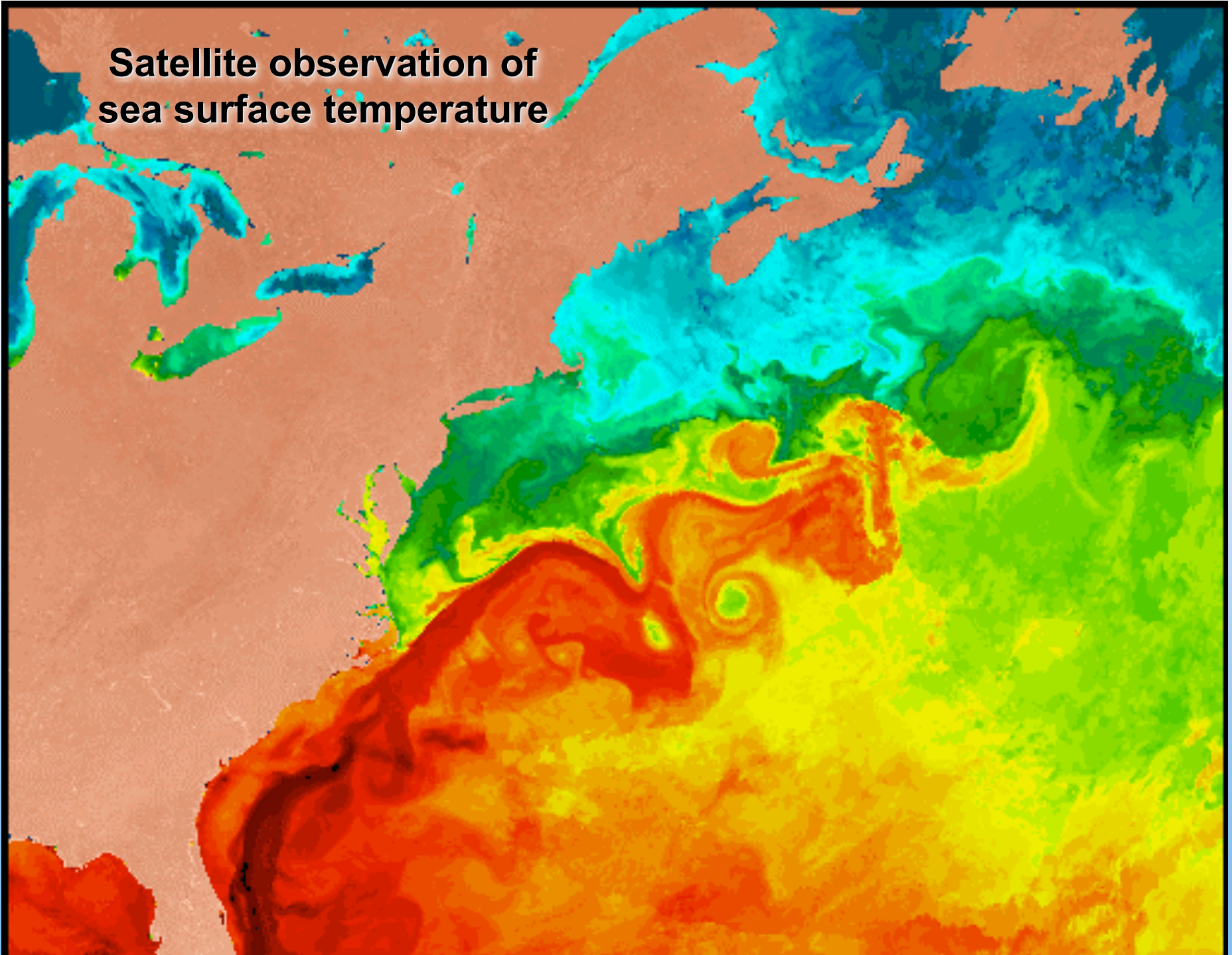- fully coupled to atmosphere, etc.

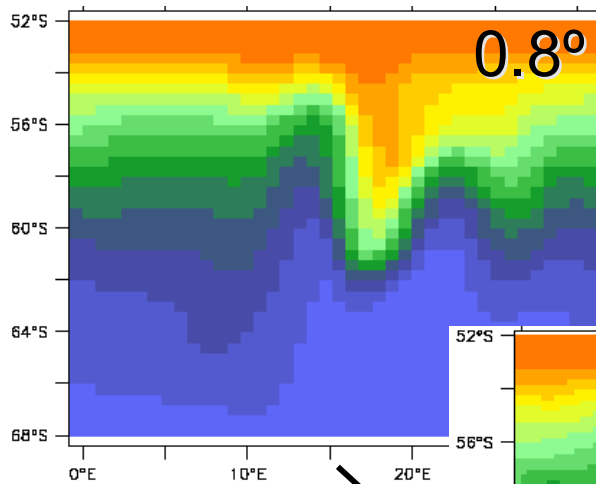Potential temperature
0.8° x 0.8° grid

Eddy-resolving sim.

- high resolution: 0.1 deg (10 km)
- short duration: 50-100 years
- ocean only

Rossby Radius of deformation

Potential temperature
0.1° x 0.1° grid

Satellite observation of sea surface temperature

What do you get with higher resolution?

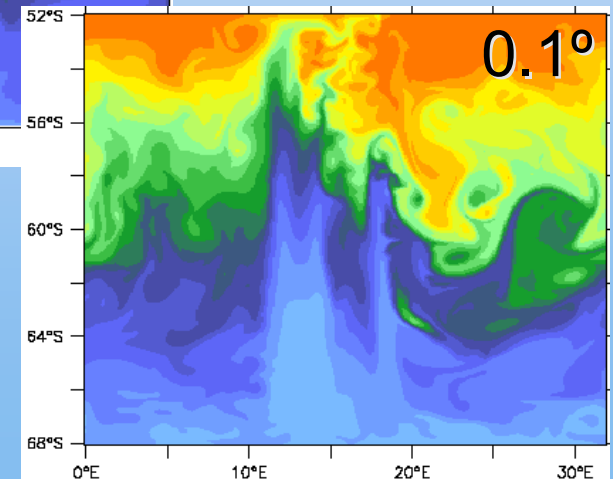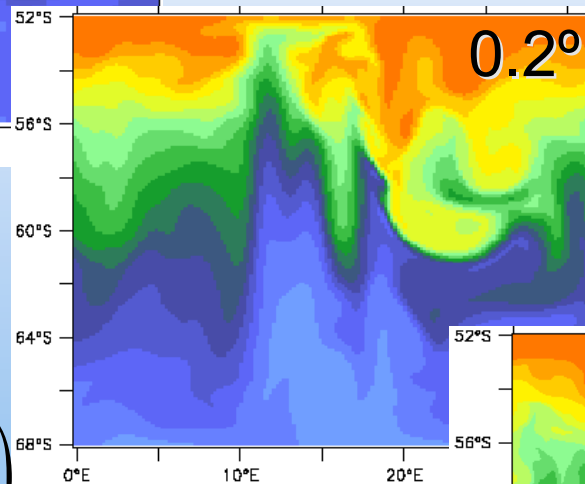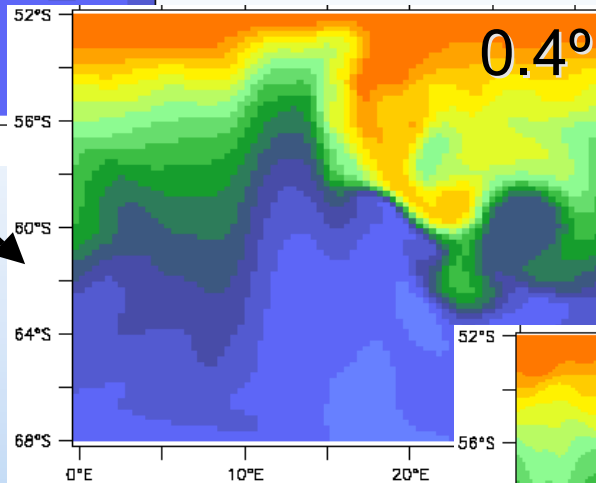Small-scale turbulence and eddies transport energy and heat.

0.8°

0.4°

0.2°

0.1°

Reynolds decomposition:

$$u = \overline{u} + u'$$

total → time average, → perturbation

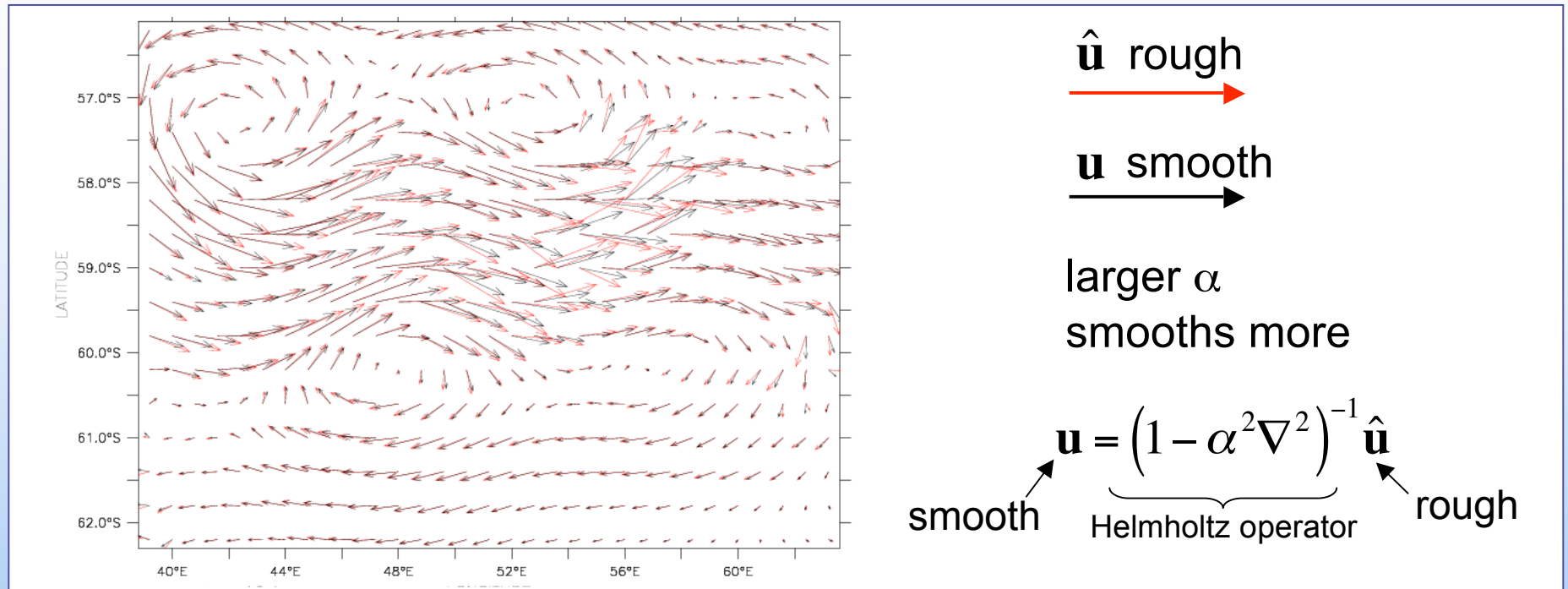cost of doubling horizontal grid is factor of 10

These become more realistic with higher resolution:

- eddy heat transport: $\overline{v'T'}$
- eddy kinetic energy: $\frac{1}{2}\left(\overline{u'^2} + \overline{v'^2}\right)$
- feedback of small-scale features on the large-scale mean flow - important for oceanic jets
- vertical temperature profile

Sub-grid scale turbulence model: LANS-alpha model
## Developed by Darryl D. Holm (CCS-2) and colleagues in 1990s

$\hat{\mathbf{u}}$ rough

$\mathbf{u}$ smooth

larger α
smooths more

$$\mathbf{u} = \left(1 - \alpha^2 \nabla^2\right)^{-1} \hat{\mathbf{u}}$$

smooth

Helmholtz operator

rough

POP-alpha

rough velocity, $\hat{\mathbf{u}}$

smooth velocity, $\mathbf{u}$

momentum equation

$$\partial_t \hat{\mathbf{u}} + \mathbf{u} \cdot \nabla \hat{\mathbf{u}} + \nabla \mathbf{u}^T \cdot \hat{\mathbf{u}} - f \times \mathbf{u} + \mathrm{metric}(\mathbf{u}) = -\rho_0^{-1} \nabla p + \mathcal{F}_H(\hat{\mathbf{u}}) + \mathcal{F}_V(\hat{\mathbf{u}})$$

advection

extra
nonlinear term

Coriolis

e.g. centrifugal

pressure
gradient

diffusion

The test problem:
Idealization of Antarctic Circumpolar Current
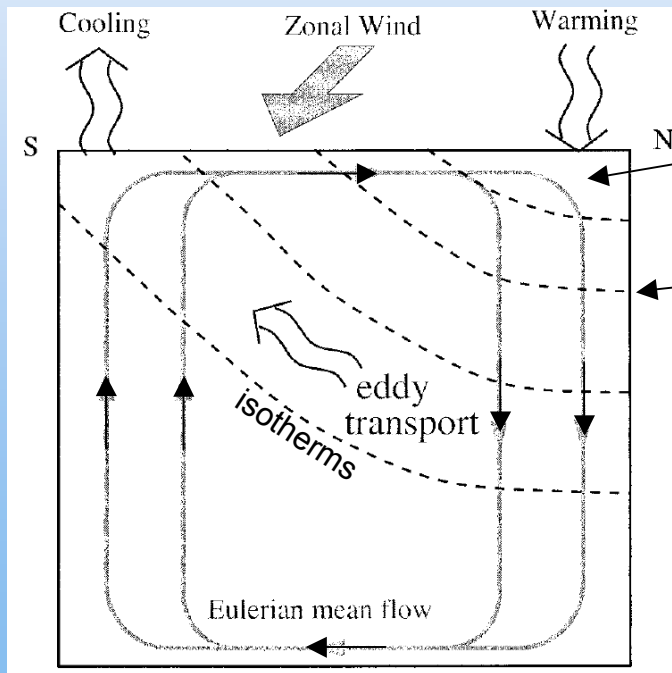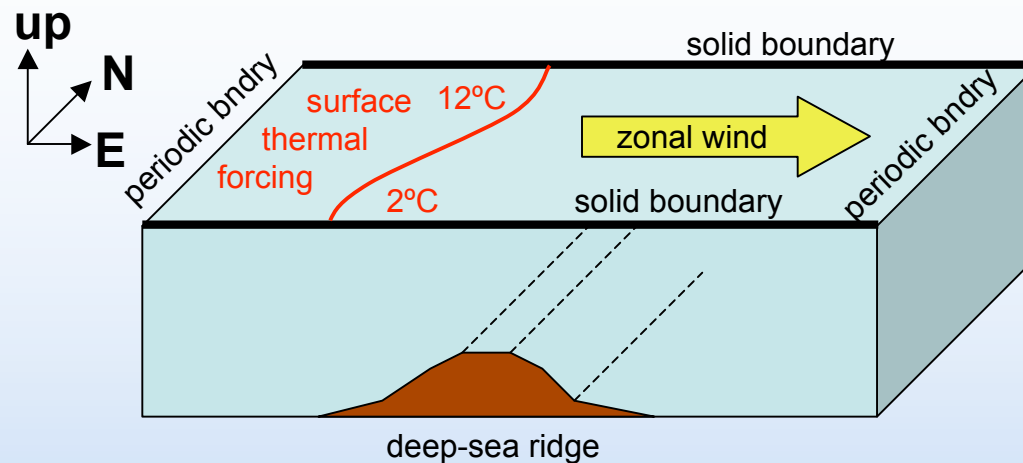
Baroclinic Instability:
1. Eastward zonal wind causes northward Ekman transport
2. Circulation tilts isotherms (lines of constant temperature)
3. Potential energy of baroclinic instability converted to kinetic energy.
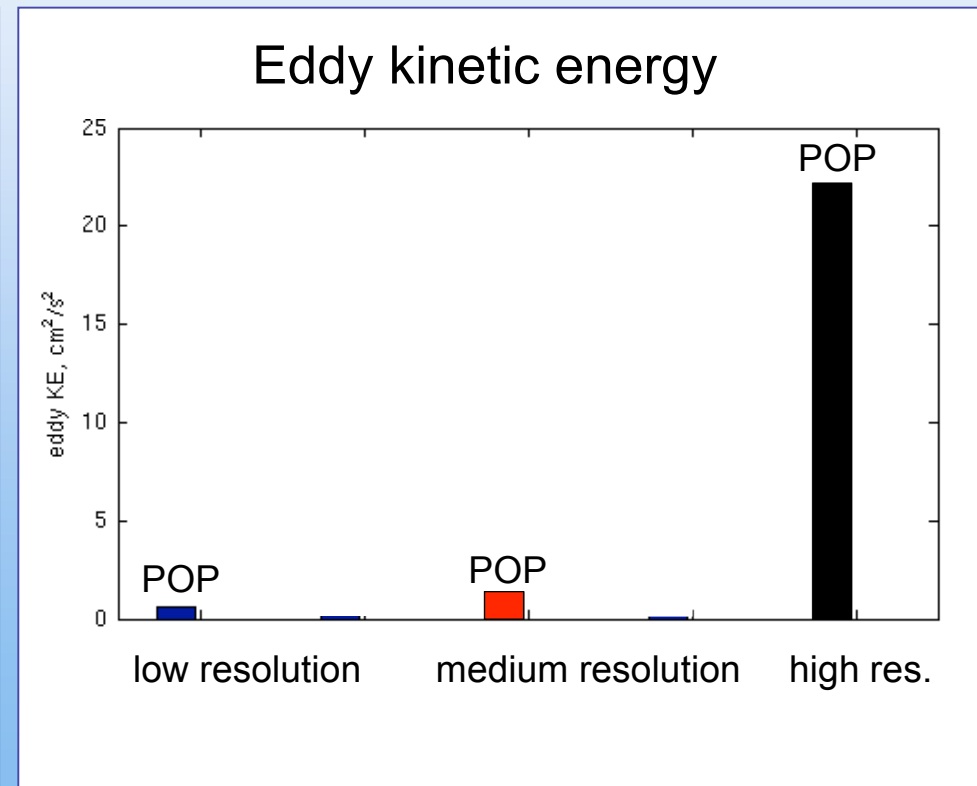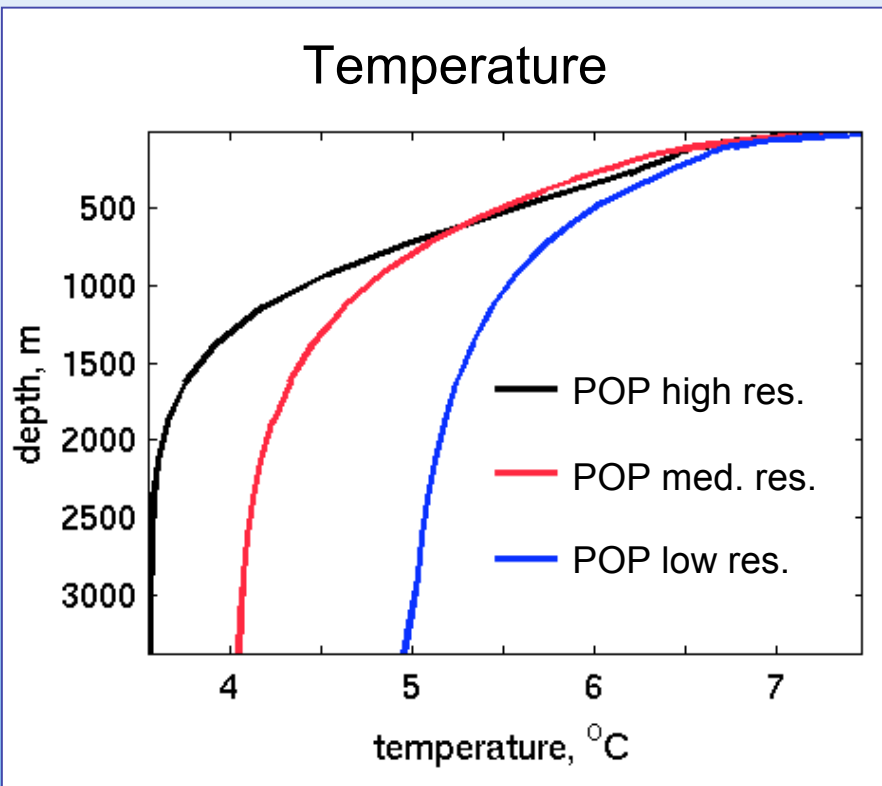4. Small scale turbulence (eddies) transport heat and kinetic energy

Thermocline depth is determined by the eddy transport quantities.

POP-alpha Results

Mark Petersen, Matthew Hecht, Darryl D. Holm, & Beth Wingate (CCS-2)

POP-alpha statistics are like higher resolution runs with standard POP in:
- vertical temperature profiles
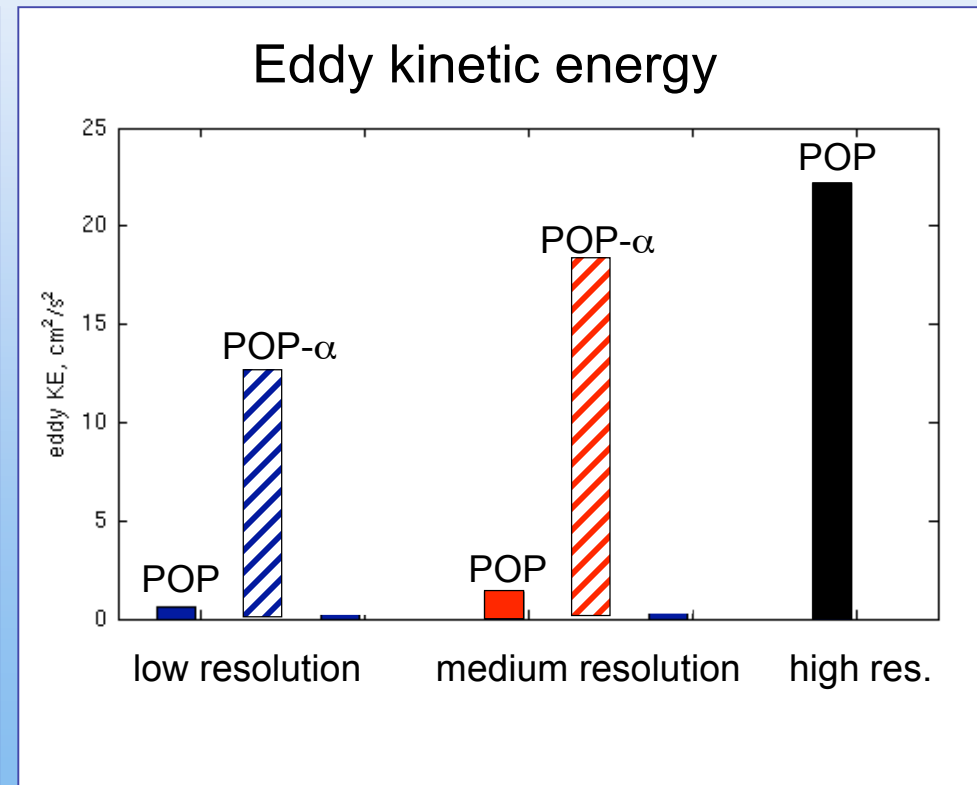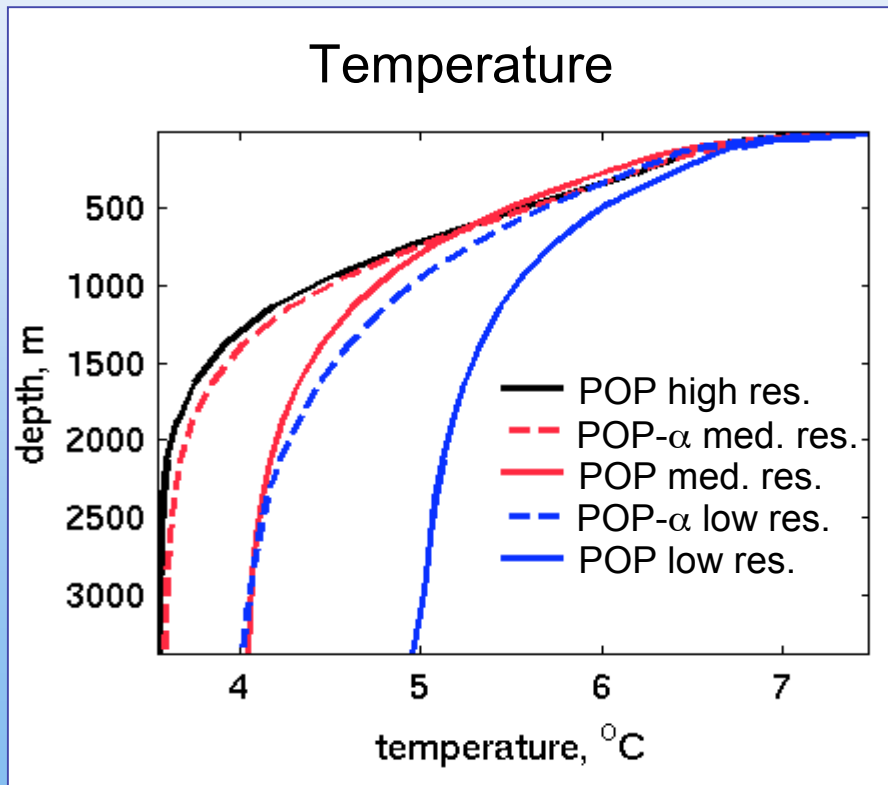- eddy kinetic energy
- kinetic energy

POP-alpha Results

Mark Petersen, Matthew Hecht, Darryl D. Holm, & Beth Wingate (CCS-2)

POP-alpha statistics are like higher resolution runs with standard POP in:
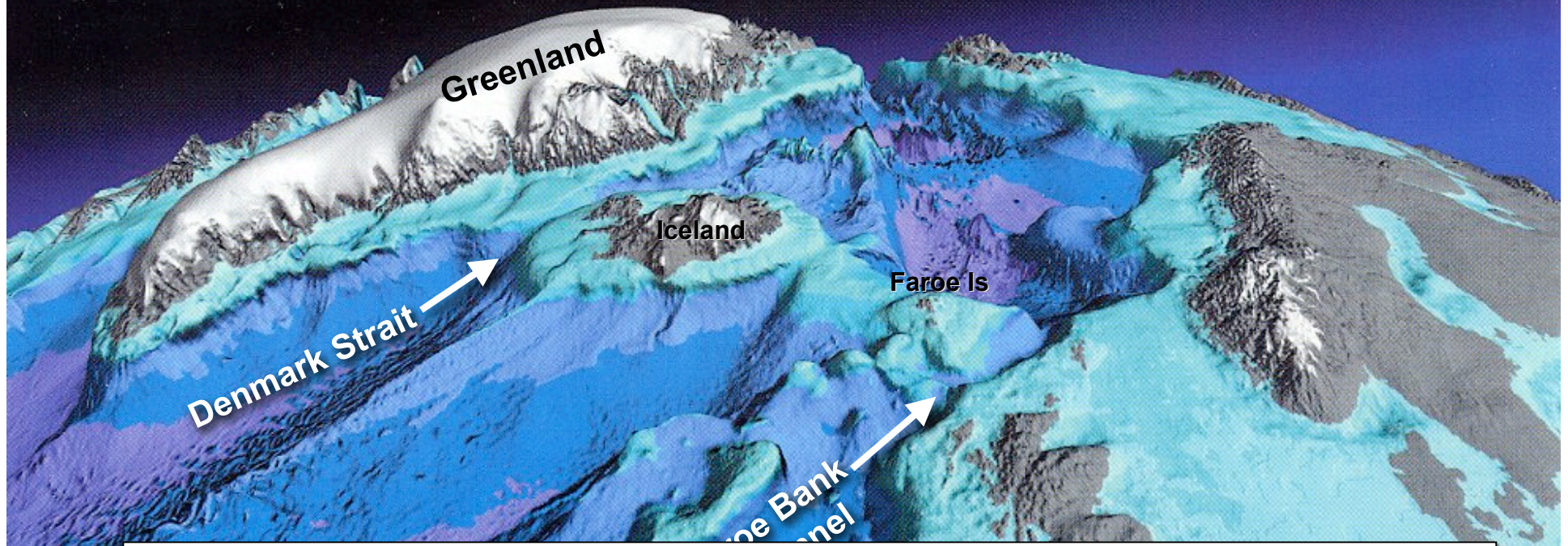- vertical temperature profiles
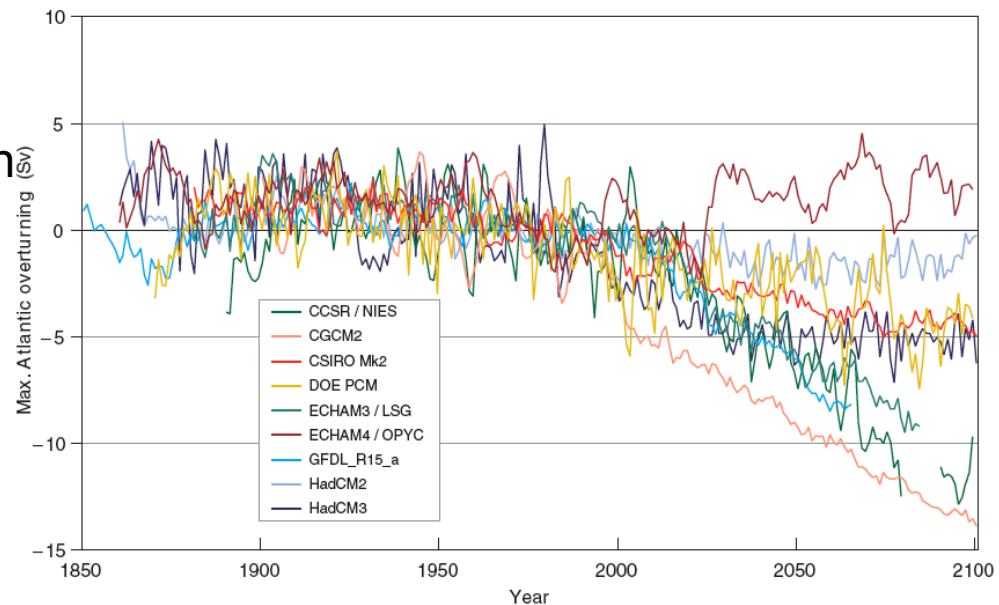- eddy kinetic energy
- kinetic energy

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Overflow regions in the North Atlantic

Greenland

Iceland

Faroe Is

Denmark Strait

oe Bank
...nel

Change in Atlantic
overturning circulation in
IPCC models.

Total circulation is
10 to 30 Sv
($1 \text{ Sv} = 10^6 \text{ m}^3/\text{s}$)

Max. Atlantic overturning (Sv)

Year

- CCSR / NIES
- CGCM2
- CSIRO Mk2
- DOE PCM
- ECHAM3 / LSG
- ECHAM4 / OPYC
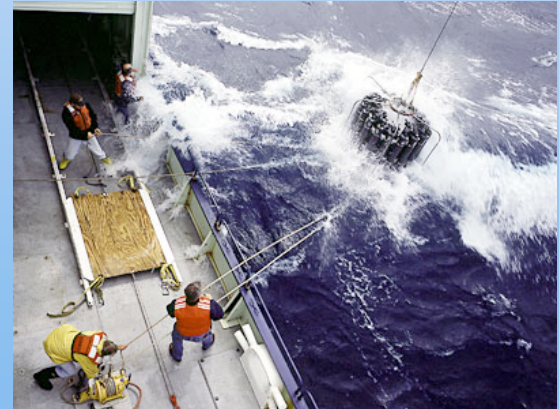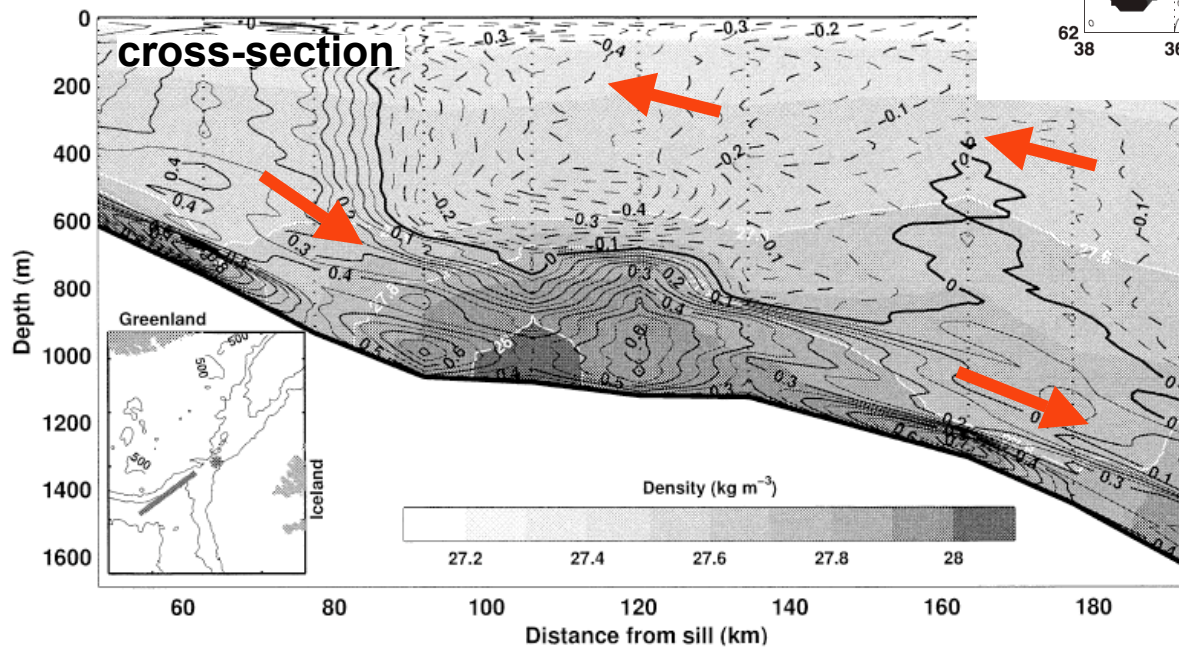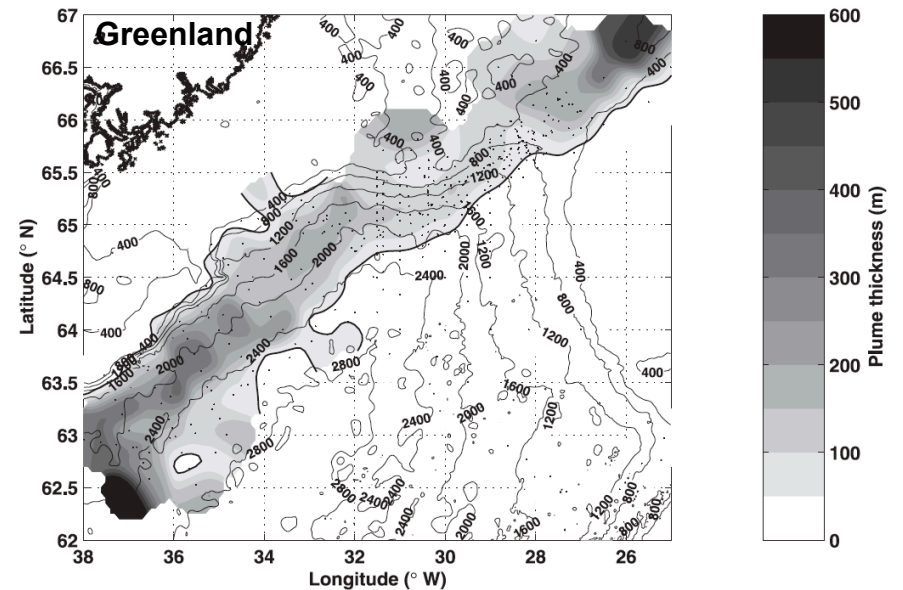- GFDL_R15_a
- HadCM2
- HadCM3

How do we study ocean overflows?

- Observations - shipboard, buoys, and autonomous floats

- Laboratory experiments

- Direct numerical simulation (DNS)

- Realistic numerical simulations

How do we study ocean overflows?

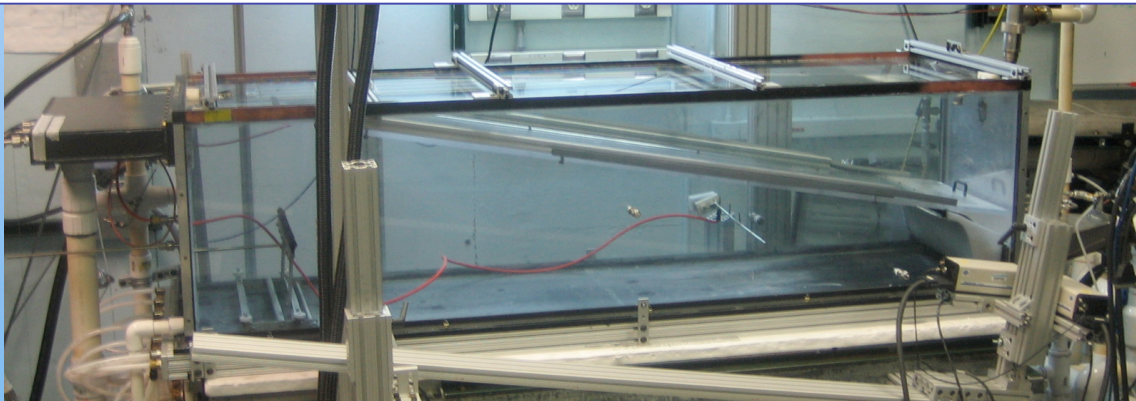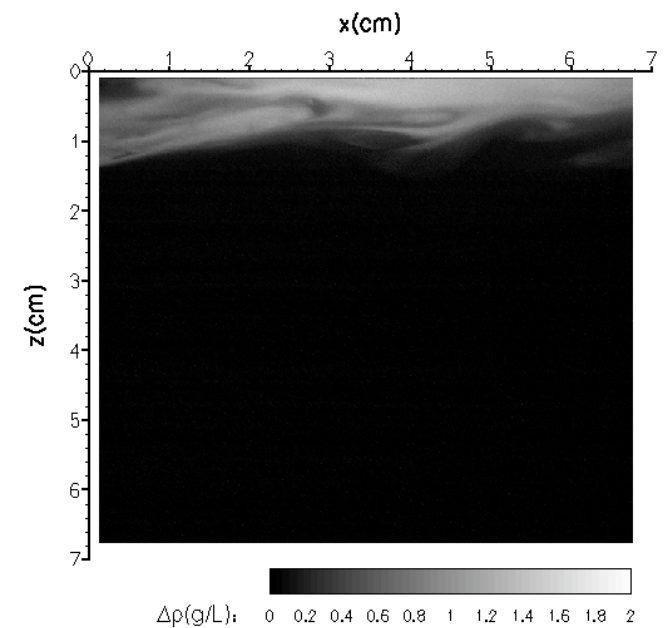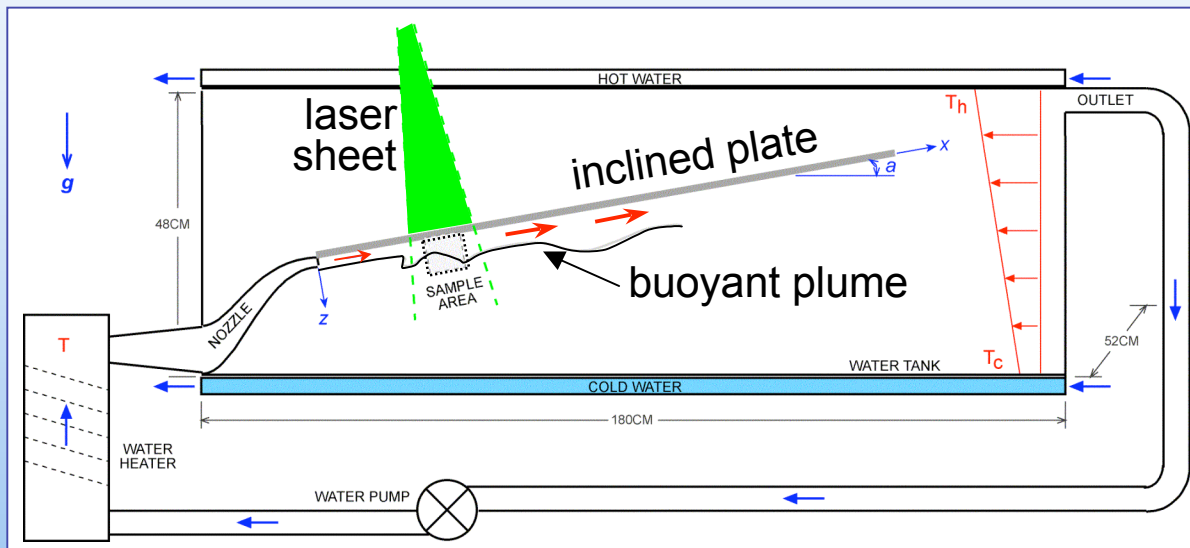- Observations - shipboard, buoys, and autonomous floats

cross-section

Girton and Sanford 2003, JPO

How do we study ocean overflows?

- **Laboratory experiments**
  Jun Chen, Philippe Odier , Mike Rivera, Bob Ecke (CNLS, MST-10)
  - Velocity measurement: Particle Image Velocimetry (PIV).
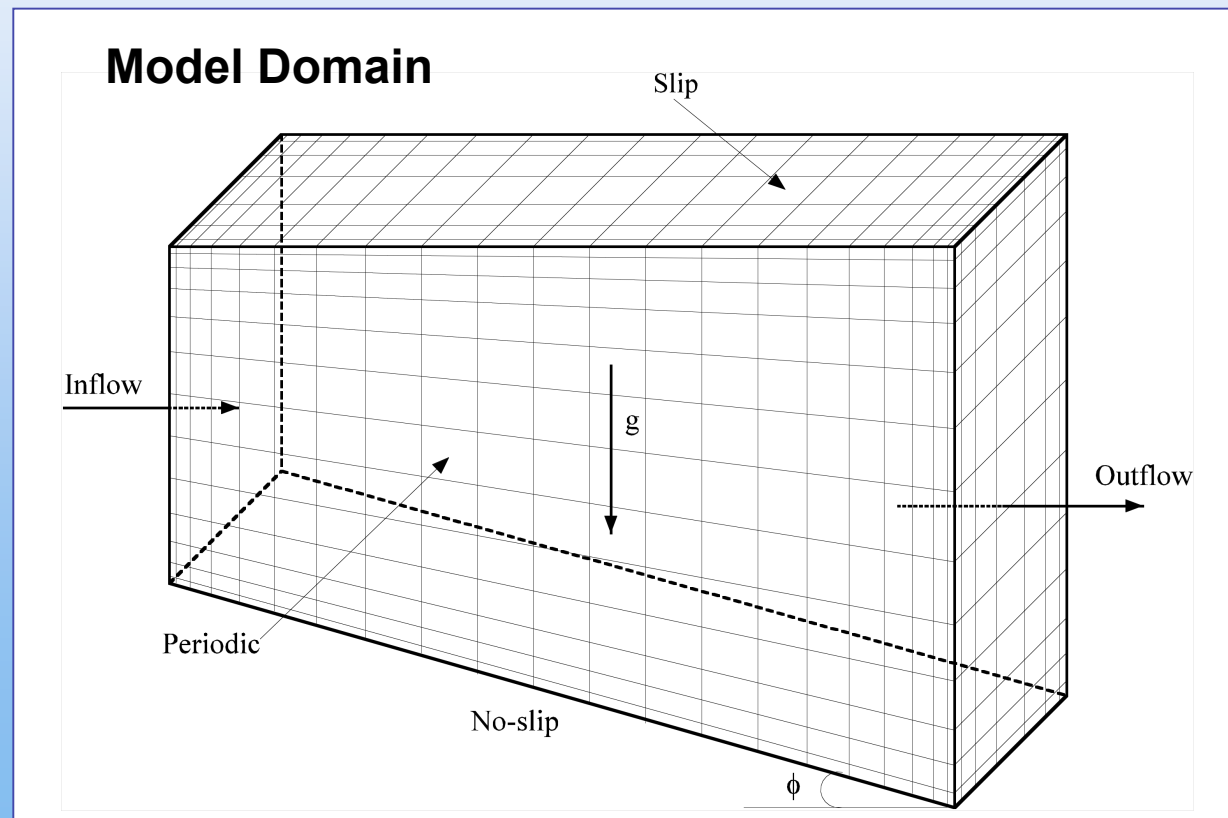 - Density measurement: Planar Laser Induced Fluorescence (PLIF).

How do we study ocean overflows?

- Direct numerical simulation (DNS)
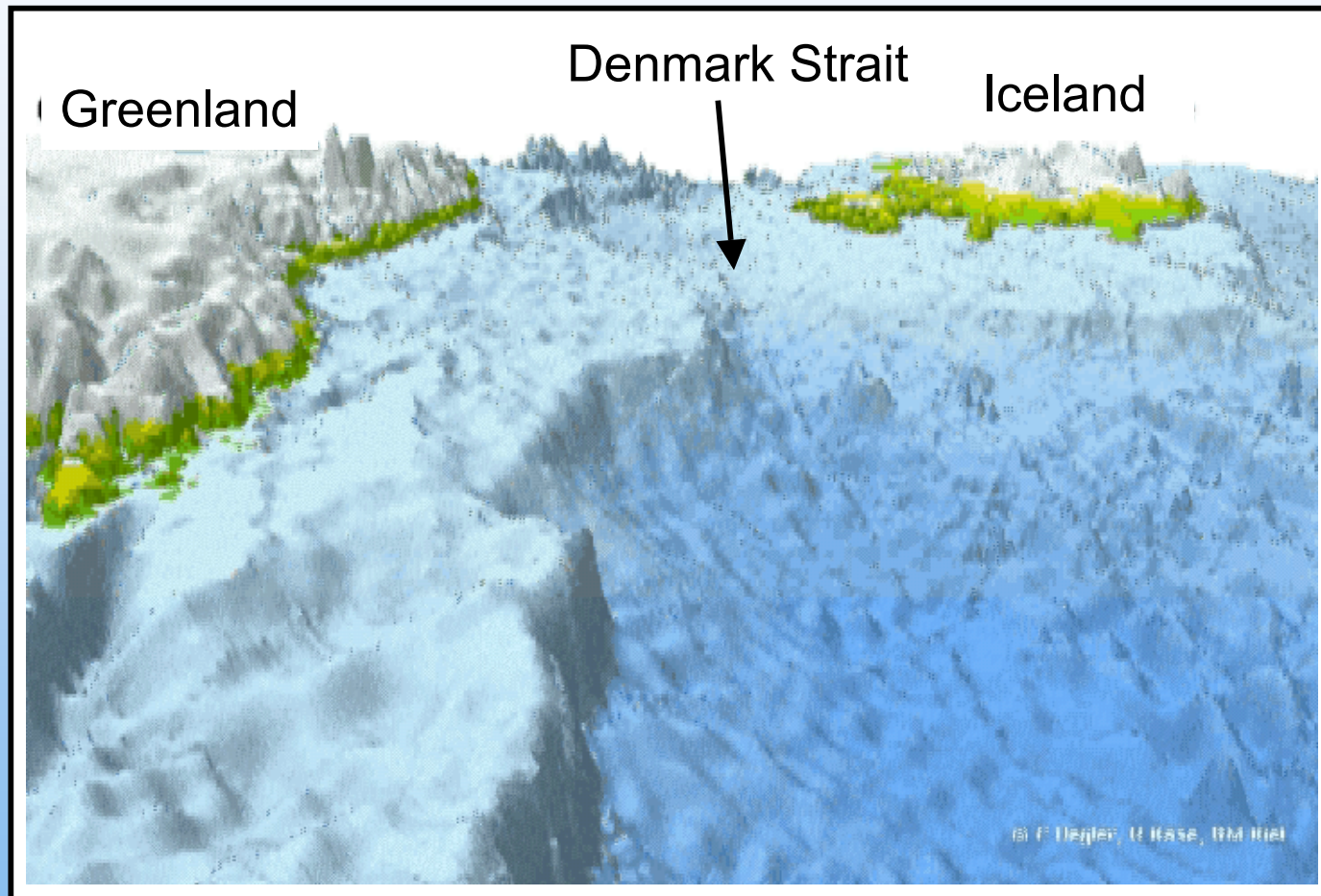 *Daniel Livescu, CCS-2*

  - Fully resolve all the relevant time and length scales.
  - No artificial dissipation or subgrid models.
  - Highly accurate numerical methods

How do we study ocean overflows?

- Realistic numerical simulations

4 km horizontal grid, dam-break initial conditions

isopycnal (density) surface
colors show thickness of overflow water

Käse et.al. 2003, *JGR*

Summary

- Higher resolution can solve all of your problems.

- You can't possibly have high enough resolution to solve your problems.

- We have to make the best of the resolution we have:
  - Mathematically based sub-grid scale parameterizations
  - Always verify with observations and experiments

- We can't possibly resolve the physics at or below the grid-scale

- We can hope to capture the effects of the sub-grid scale on the larger scales, like:
  - Global circulation and heat transport
  - Location of jets (Gulf Stream)
  - Properties of water masses (Temperature and Salinity)